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V.N.Shlyaptsev[1], J.Dunn[2], S.Moon[2], A.L.Osterheld[2], J.J.Rocca[3], F.Detering[4], W.Rozmus[4,5], J. P. Matte[6], H.Fiedorowicz[7], A.Bartnik[7] and M.Kanouff[8]

[1]UC Davis, DAS / ILSA / LLNL, Livermore, CA, 94550,
[2]LLNL, Livermore, CA, 94550,
[3]Colorado State University, Ft.Collins, CO, 80523
[4]University of Alberta, Dept. of Physics, Edmonton, Alberta, Canada
[5]ILSA / LLNL, Livermore, CA, 94550,
[6]INRS-Energie, CP 1020, Varennes, Québec J3X IS2, Canada
[7]Institute of Optoelectronics, Military University of Technology, Warsaw, Poland
[8]Sandia National Lab, Livermore, CA, 94550

ABSTRACT. In this work we report numerical modeling results of laser-generated transient inversion and capillary discharge X-ray lasers. We have found the importance of plasma kinetics approaches in transient X-ray lasers physics by expanding the physical model beyond hydrodynamics approximation. Using Particle and Fokker-Planck codes the clear evidence of the Langdon effect was inferred from the recent experimental data obtained with the Ni-like Pd X-ray laser. In the search for more efficient X-ray lasers we looked closely at alternative target designs utilizing low density targets. In conjunction with recent experiments at LLNL the numerical investigations of gas puff targets has been performed.

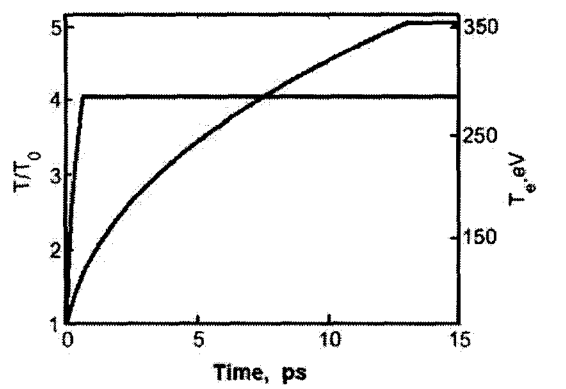
Introduction

In recent years quite noticeable progress has been achieved in the development of several types of table-top X-ray lasers. Among them the transient collisional excitation X-ray lasers driven by short-pulse laser systems and the small current capillary discharge lasers were developing fairly rapidly. There exist significant interest in substantial increasing of efficiency and extending the operation of transient and discharge pumped X-ray lasers to shorter wavelengths. Here detailed numerical calculations can be specifically valuable for ongoing experiment. The numerical modeling of these lasers allowed us to reproduce main characteristics and suggest additional routes of their further improvements. We discuss here new approaches in this direction which are under development in the LLNL, Colorado State University and other labs. Our recent results of numerical investigation of plasma evolution, amplification dynamics, atomic kinetics and diagnostics of laser active medium of these lasers are reported.

1. Influence of pulse duration on transient x-ray lasers

After the demonstration of transient X-ray lasers, experiments and modeling devoted substantial time for the optimization of laser-target design in very broad space of parameters. Many different elements and their ion stages were investigated as well as different combinations of pre-pulse and short (main) pulse intensities, wavelengths and pulse durations. The theoretical and numerical research was devoted both to explain the data based on current knowledge in plasma physics and numerical analysis and then to predict future directions of advanced research.

We discuss here one interesting finding with 147A Ni-like Pd X-ray laser where X-ray laser represented an object of investigation and powerful diagnostic tool at the same time. Keeping short pulse laser pumping energy constant ~5 J, the pulse duration (and hence flux density) were varied [1] in a very wide range from 0.6ps to 24 ps. After numerical modeling of these experiments with code RADEX we found that simulations successfully reproduce X-ray laser parameters at the longer pulse durations. But we got substantial contradiction with experiment in the short pulse end of durations 0.6-1.2ps which, contrary to the experiment, did not exhibited X-ray output decline. The longer pulse cases with 13ps and 24 ps pulse durations also showed decrease of the x-ray laser output in accordance with experiment [1]. While clearly latter is an effect of specific implementation of traveling wave with 7ps segments and increased mismatch with duration of transient gain, which is of the order of 5-7 ps, the intensity decrease at shorter duration had no reasonable explanation. It is very interesting to note that hydrocodes produce almost identical, within 1-2%, plasma parameters at electron densities ~10^{20} cm^{-3}, which are optimal for lasing, independently of pumping laser pulse duration even in much broader range of durations



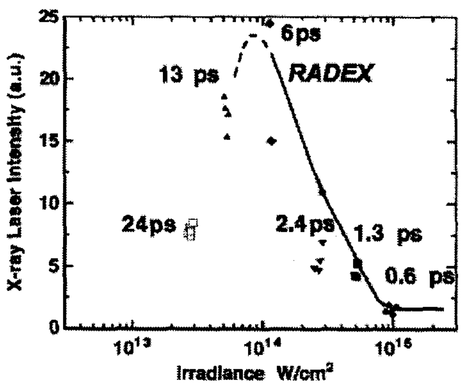


Fig. 1. Particle code calculations of electron temperature evolution of plasma irradiated by two different pulses 0.6ps at 10^{15} W/cm^2 and 13ps at 5×10^{13} W/cm^2 with the equal laser energy per pulse ~ 5J. The value of initial temperature T_0=70eV is not critical for final temperature.

Fig. 2. Experimental (squares, triangles, diamond, dots) and numerical (solid line) X-ray laser signal vs pumping pulse flux (which is here inv. proportional to duration). Dashed part of RADEX calculation curve takes into account the gain duration to traveling wave stepping mismatch

between 100 fs and100 ps if its energy is kept constant. During analysis of plasma at these so different pulse durations we found that the differences in heat conduction and the influence of hot electrons on excitation and ionization during gain life-time were estimated to be negligible. The heat conduction remains almost classical due to small ratio of electron mean free path to temperature gradient length at the distances as far as 30-70 microns from the target where amplification takes place. Essentially, all hydro plasma parameters during very short gain duration of transient gain remain almost constant. The short duration of the transient inversion also ensures ionization is almost frozen during amplification. Hence hydrodynamics of plasma with its relatively large characteristic timescales did not provide substantial evidences to explain the decline of X-ray laser output at shorter pulse durations.

Analyzing processes with shorter timescales we found that the electron-ion $\tau_{ei} \sim 0.3$ ps and electron-electron $\tau_e = Z \times \tau_{ei} \sim 5$ ps collision times are not as small compared to heating laser pulse duration when it shortens towards 0.6ps. The key process responsible for explanation of this situation was found in the work of Langdon [2] who noticed that in high-Z plasmas due to the differences of noted electron collision times, the non-Maxwellian distribution function can be formed at laser fluxes Z times smaller than those corresponding to $v_q^2/v_e^2 \sim 1$. Here v_q is the maximum of the electron quiver velocity in laser field and v_e is electron thermal speed and this ratio defines heating per e-e collision compared to thermal energy or rate of deviation from Maxwellian distribution. As a result, the distribution function $\sim \exp(-v^5)$ will substantially deviate from Maxwellian which ultimately decreases inverse-bremsstrahlung absorption by a factor ~ 0.5. This is exactly what is happening in our case where we have pulse duration shorter than ~5 ps and hence laser fluxes larger than $q \sim 1.2 \times 10^{14}$ W/cm^2 when $v_q \sim 3 \times 10^8$ cm/s and $v_e \sim 1.2 \times 10^9$ cm/s.

Unfortunately treating plasma kinetics processes numerically for up to 20 - 40 ps with modern direct PIC codes, even in 1-D, usually requires extremely long processing times not available at this moment [3]. Hence, we oriented on two other approaches based on particle code with Langevin equation and Fokker-Planck methods [4, 5]. The results of this calculation of electron temperature as a function of time for short laser pulse (0.6ps) and long laser pulse (13ps) duration cases based on the first approach are shown on Fig. 1. As we see from Fig. 1, the electron temperatures are between 290eV and 360eV respectively for these limiting cases. The PIC simulation showed that electron distribution function relaxes to becomes almost Maxwellian in just 2-3 ps after the laser pulse ends. For longer pulses starting with than 13 ps the temperature does not change any noticeably (for 24 ps pulse the temperature is 380 eV) because at lower fluxes the electron distribution function is essentially Maxwellian. Based on these calculations, the atomic kinetics and ray-tracing code RADEX have well reproduced the behavior of X-ray laser intensity versus flux of our previously reported work [1], see Fig. 2. Note that decreased at short pulse durations absorption not necessarily is bad for X-ray lasers, it might be even beneficiary, for example, in the cases of longitudinal pumping.

2. Dense laser plasma x-ray interferometry and modeling

Both capillary discharge and transient table-top lasers finally achieved the stage where they can demonstrate their ability to be used in applications. One of most important of them is diagnostics high density plasmas using coherence properties of X-ray laser radiation. And already first recent works utilizing these lasers [6,7] brought very valuable and surprising results. The density profiles obtained in [6] show considerable inhomogeneities which look as suppression of density in the middle of expanding plasma. With relatively small fluxes $\sim 10^{11}$ - 10^{13} W/cm^2 with ~10ns pulse durations the experiment found that density in on-axis suppression region drop up to an order of magnitude compared to surrounding plasma. Though axial jets and filaments in plasma were reported in numerous experimental works earlier, the formation of inhomogeneities of density profile of such large magnitude at such parameters was never seen before. To shed the light on so unusual plasma behavior we are currently performing simulations with codes LASNEX and RADEX.

Another unusual plasma parameter was the value of maximum density in side lobes which at 10^{13} W/cm^2 fluxes approach critical one $n_c=10^{21}$ cm^{-3} at the 150-200 micron away from the 30 microns wide focal spot which may appear as an obvious contradiction with classical steady-state spherical plasma expansion under the influence of laser radiation and even world modeling practice. Our 1-D and 2-D modeling ruled out the possibility of ponderomotive force, saturation of electron heat conductivity and additional pre-heat inside expanded plasma column far away from the surface as primary reasons for this density distribution with suppression.

Investigating first the cases with line focus geometry at smaller fluxes ~10^{11} W/cm^2 we found that velocity of central and hotter on-axis part plasma, formed by large pressure gradient near the critical surface, achieves (5-6) × 10^6 cm/s while in off-spot regions of smaller gradients it moves at several times lower speeds gradually increasing up to (2-3) × 10^6 cm/s. The speed differences hence define the dynamics of high-density plasma peaks which do not appear or are less pronounced at earlier times until they reach distances ~100-200 microns from the target as observed in the experiment. After extensive analysis it was found that there is no contradiction with previous and current modeling. The minimum of the density, positioned on-axis along the normal to the target surface, corresponds to the regular expansion of illuminated part of plasma, the parameters of which are strongly governed via inverse bremsstrahlung absorption by the laser wavelength. This part of density profile fits well to both 1-D or 2-D hydrodynamics models description of sub-critical density and velocity evolution of plasmas under laser irradiation, while the unusually large density peaks accompanying the minimum are, in fact, represent colder material expansion formed outside the focal spot. Side peaks are produced by lateral (along the surface, or Z-axis, as in Fig 3) mass expansion and heat conduction and XUV radiation emitted from hotter focal spot area. As it can be seen from Fig.3, this side mass and energy flow effectively increases ablation area ~3-4 times compared to initial one. Such off-spot energy deposition represents a purely 2-D effect, and peaks of maximum density do not depend directly on the laser wavelength. Additionally, the critical density for XUV radiation is much larger than it is for laser radiation ~10^{21} cm^{-3} while laser radiation is contained in the suppressed density channel, hence the side peaks values are not limited by n_c and potentially can grow even further what we see in the experiments with spot focus geometry at fluxes ~10^{13} W/cm^2.

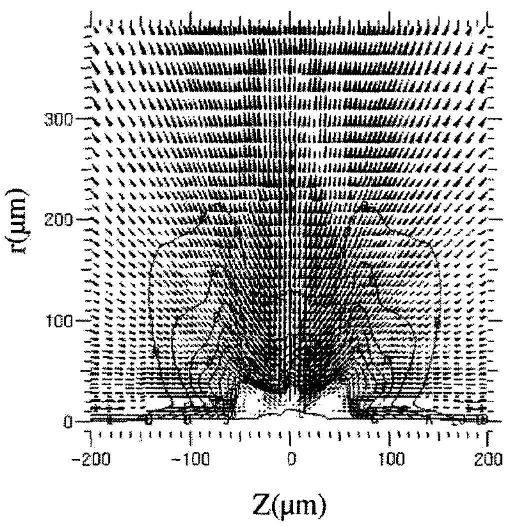


Fig. 3. Electron density contours and velocity vector plot for the line focus plasma at 8.5 ns after the beginning of the Nd-YAG laser pulse computed by LASNEX. The laser intensity is 10^{11} W/cm^2, spot line width 30 um and the laser pulse width is assumed to be 10 ns. All isodensity contours differ by 1×10^{19} cm^{-3} with the most external one corresponding to 10^{19} cm^{-3}.

Qualitatively similar density lobes, but of much smaller magnitude were also revealed in another interferometric experiments this time utilizing transient X-ray laser at LLNL [7]. Due to lower Z, much shorter laser pulse duration and expansion time before probing, and wider spot size, they were less pronounced. Radex 1-D calculations of density agree well with this experimental data of laser plasma expansion, since along the normal to the surface the expansion can be well described in cylindrical or spherical 1-D approximation for line or spot focus respectively. Due to high accuracy the X-ray laser interferomentric data this method will become very important not only for experiment and plasma diagnostics but for the development and validation of hydrocodes and plasma theory as well.

3. Gas puff transient X-ray lasers

Low density targets (such as foams, gases, vapors, clusters, pre-pulse formed plasmas, even dusts, etc) have attracted the attention of theory and experiment because of their appeal as an almost 'ideal' active medium for XUV lasers [8,9]. Recent experimental demonstration of picosecond-driven lasing in Ne-like Argon with gas puff targets [10] allowed us to obtain additional knowledge which allowed us to shed light on some unknown properties of gas-puff. One of the important facts which was determined in this work suggests that gas puff produces substantially larger densities than it was expected initially. For example quite large refraction with deflection angle of output radiation for this transient X-ray laser, of the order of 26-30 mrad, indicates that the optimal lasing conditions were formed at the electron density ~4×10^{20} cm^{-3} corresponding to particle pressures ~1.5atm at the nozzle exit, i.e. 3-5 times larger then it was expected to be optimal. Calculations of the flow of the gas from the nozzle qualitatively confirm the possibilities of larger gas densities at which our X-ray laser operates [11]. Calculations of unsteady flow in which the density is varying depending on time delay from valve opening are under the progress.

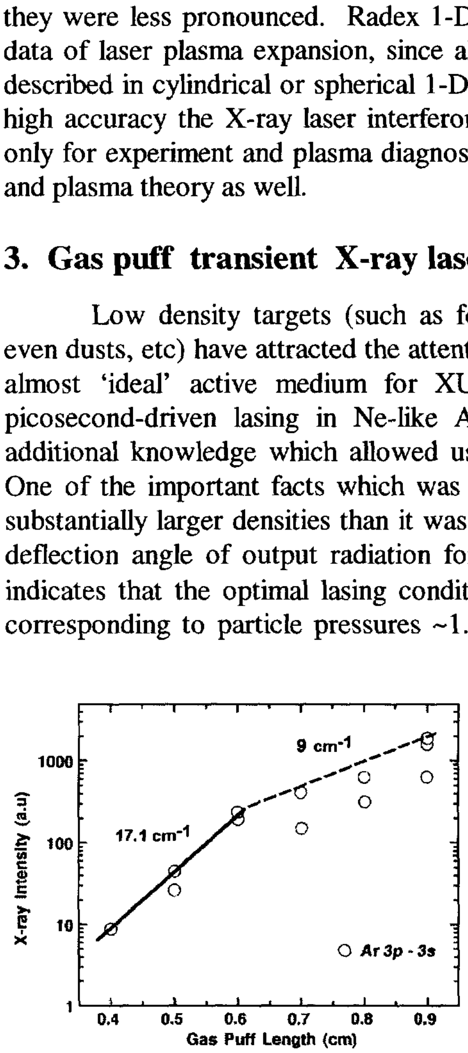


Fig. 4. Experimental (dots) and numerical (solid line) X-ray laser signal vs length. Dashed curve of different slope is indication of substantial refraction

RADEX modeling shows that when gas pressure at the nozzle exceeds 1.2 atm the plasma forms shock-like structure where absorption of following main pulse is much more effective and lasing takes place on the slope of density profile. The gain duration in Ne-like Argon is ~5-6 ps, with gain reaching 15-18 cm^{-1}, the value which fits well to experiment as it can be seen from initial slope of experimental curve up to 5-6 mm after which mentioned above substantial refraction (and potentially large inhomogeneities) tamper the intensity (see Fig.4 and also [11]). Note also, that RADEX modeling reveal that the gain values as above are indication of transient inversion formation in the conditions of simultaneous ionization (which is longer then inversion life-time) of lower Z ions before Ne-like ArIX and hence our low intensity prepulse was not sufficient to ionize plasma up to Ne-like stage. This is somewhat similar to the situation with so called prepulse technique transient lasers [12-14] which actually are operating in transient regime too. The fact that best X-ray laser signal was obtained with the maximum energy of the available prepulse is also possible confirmation of conditions that plasma was not ionized to right state. It is clear that conditions in current gas puff configuration are not optimal to get refraction minimized (hence we get different slope as in the dashed part of the curve in Fig.4). Further investigation of absorption efficiency and ionization dynamics hence is crucial for better understanding of plasma formation in gas puff targets.

4. Acknowledgments

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